WEAR OF UNLUBRICATED STEEL SURFACES

DONALD M. KIRKPATRICK

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Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

United States Naval Postgraduate School
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ABSTRACT

An investigation was made of the wear, under varying conditions of load and speed, of an annealed steel finger held against a rotating hardened steel sleeve. Measurement of the wear was made by weight and volume change of the finger, whereas measurement of the transfer to the sleeve was made by its increase in weight or, on separate runs, by its increase in radioactivity. The atmosphere was dry air.

The purpose of this work was to inspect an elementary wear process and accompanying transfer of metal under simple controlled conditions with a view to separating out the various component processes which are collectively known as wear. By this process it is hoped to determine more of the "why" of wear. This was done by a previously accomplished radioactive technique and also by a corroborative weight change technique.

The writer wishes to express gratitude and appreciation to his thesis adviser, Professor Ernest K. Gatcombe, for encouragement and advice in the accomplishment of this work, and to Professor William W. Hawes for his assistance and advice in connection with the radioactive phase of the work.

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1. Introduction

(A) SPECIFIC LACK OF WEAR INFORMATION

Recent years have seen an increase in the effort to find some definite and practical empirical rules of wear that the practicing engineer can employ in the design of mating machinery parts. In almost every field of mechanical engineering, the engineer can turn to a thumb rule or law to guide him in design work. An example of one such law, very akin to wear, is Coulomb's law of friction. In spite of much effort in the field of wear, and the advancement of various theories on the mechanisms of the wear process, only very few definite wear relationships have been developed, along with a few certain qualitative rules of wear. These efforts have included attack from various aspects such as particle size, energy level, and various ratios of material properties. Since so many variables exist, known and unknown, dimensional analysis has not been a fruitful approach. Unfortunately also, no standardization of approach exists so that the useful data that does exist cannot be easily correlated.

(B) RECENT INVESTIGATION

Bowden and Tabor [2] showed through electrical conductance experiments that the area of real contact between two mating surfaces was never more than 1/100 of the area of apparent contact and could be as little as 1/100,000 of it, and that the contact is between surface asperities which individually are under variable loads. The topmost asperities will assume load first and deform, permitting load to come on smaller asperities until the whole load is assumed throughout the area at various junctions, each junction carrying a slightly different portion of the total load. On the basis of the above, they say:

Friction is essentially the shear strength and adhesion the

tensile strength of the junctions formed at the regions of real contact.

They also observed that pressures were extremely high as a result of the small area of actual contact and that, as a result, when two metals were placed together they cold weld on the asperities. This cold weld is not observed except under controlled laboratory conditions since every metal surface has a film over it which prevents proper metal to metal contact. Similarly when metal slides on metal, welding takes place which provides the familiar friction force due to the breaking of these welds. This welding these workers call adhesion and is generally regarded as a fundamental and prime cause of wear, present even when all other forms of wear, such as corrosion, abrasion, are very carefully excluded between two metal surfaces.

Concerning temperatures at the interface between asperities, Bowden and Tabor have shown that minute flashes (on the order of 2 microseconds) of temperatures of 500°C occur very easily even at very low loads and speeds, even though the bulk of the rubbing materials is cool. This temperature is normally limited by the melting point of the material but exceptions occur, as for instance in an exothermal oxidizing process in which additional heat is given off in the oxidation process. Then temperatures of 2000°C and more can occur.

(C) TWO RECENT WEAR THEORIES

Recognizing the fact that the wear process is complex, various workers have attempted to break it down into component parts, as elementary known mechanisms. Feng [8] explains that the high spots on two surfaces are roughened as the result of plastic deformation and this roughening gives an interlocking effect which is the primary cause of

metal transfer and wear. Tangential forces break off the asperities below the top, since the top is stronger due to strain hardening. This breaking off of the asperities produces a flash of temperature. The broken off piece can either be welded to the other metal asperity or can break off completely and become a loose wear particle. Feng says that, while in the initial stages there is metal to metal contact between the asperities, subsequently the high temperature causes chemical reaction at or near the asperity top where the temperature is a maximum, and that a film is formed which then becomes the wearing surface.

M. Kerridge [10] in a more recent explanation of the wear process has proposed the theory that when the asperities are forced together, localized welding takes place and the softer metal is transferred to the harder metal. A layer of this softer metal is built up on the harder surface, and this layer is then oxidized and finally removed as wear debris.

These two theories have certain aspects in common, namely, that very high temperatures exist and that transfer from soft to hard material takes place at even the very lowest loads, speeds, and distances. However the basic difference between the two theories is that Feng says that his proposed mechanism explains the welding of the sheared off peaks as the consequence of friction, whereas Kerridge's "welding" is considered the cause of friction.

(D) THE PURPOSE OF THIS INVESTIGATION

The purpose of this paper is to corroborate independently the work of Kerridge, using a technique which is similar. He used a radioactive soft steel finger rubbing against a harder steel ring and observed carefully the increase in activity of the initially inert ring. He found that the activity increased quite rapidly and at the same rate, initially, as the

wear rate, but reached an equilibrium condition after which no activity increase was noted. Yet when an inert pin was substituted, the activity dropped off very quickly, indicating that the transfer process was a continuing one. The particle membership of the ring was constantly changing, at equilibrium more being added from the active pin, and at the same time loose wear debris being dropped from the ring. No evidence existed that any wear debris was formed directly from the soft pin without first being deposited on the harder ring. Also there seemed to be no back transfer from hard to soft metal as indicated by complete lack of radioactivity of the inert soft pin when inserted after running some time with the active pin.

2. Apparatus and Materials

(A) THE TEST MACHINE AND ATMOSPHERE CONTROL

The Amsler Wear Test Machine used for the tests is shown in Figure 9. The machine was modified so as to eliminate its loading and measuring systems except for the shaft revolution counter; one drive shaft was disconnected and used to mount the stationery finger holder, finger, and weights. The other shaft and motor were used to drive a hardened steel sleeve taper mounted on an inner shaft adapter. These may be seen in Figure 10. The finger and the sleeve were the two mating surfaces in the tests.

A round air tight atmospheric chamber was provided to cover the sleeve and finger during the tests so that the atmosphere could be controlled. The sealed entry into the chamber for the finger and finger holder was provided by a skirt, attached to the outside of the finger shaft, which was immersed in an annular light oil bath mounted around the entry hole of the chamber. The atmospheric chamber with hoses attached can be seen in Figure 11. One end of the chamber was mounted on the machine and provision was made for threading the rest of the chamber onto this end.

(B) DESCRIPTION OF WEAR PIECES

The fingers were made from the same bar of 1015 normalized steel. The dimension of the rubbing face was .50 inches on each side. The rubbing surface was ground on a surface grinder as the last step in manufacture and then they were lapped to a flat with 4/0 metallographic paper on optically flat glass. They were lastly checked for flatness by the use of an interferometer. Considerable effort was made to lap them on a conventional lapping plate. This was unsuccessful due to the small size

of their face and inability to hold them from tilting during lapping. The finger hardness was 42 Rockwell B and their surface finish was 4-6 microinches rms as given by a Brush Surface Analyzer.

The sleeve, which was the rotating member, was manufactured of .85-.95% carbon, non-deforming tool steel containing manganese 1.30-1.50%, silicon .20-.30%, and molybdenum .20-.30%; it was heat treated by oil quenching from 1525°F and then stress relieving at 400°F for ten minutes. Its outer diameter was 4.0 inches and its maximum thickness was .080 inches. Its outer wearing surface was ground to 4-6 micro-inches rms surface finish. Approximately .003 inches were ground off subsequent to each test to provide the same starting finish for each test. Its inner diameter was taper ground to mate with the taper grind on the mounting adapter. It was held in place during the tests by a large washer with a diameter slightly smaller than the sleeve outer diameter. The assembly of the sleeve ready for test can be seen in Figure 10. The hardness of the sleeve was 55 Rockwell C. It was intended to leave the sleeve as quenched with a hardness of 64 Rockwell C, but the first sleeve broke in grinding so it was necessary to stress relieve it.

(C) CALIBRATION OF FINGER RADIOACTIVITY

Fingers for the radioactive tests were prepared for test and then sent to the Oak Ridge National Laboratory, Oak Ridge, Tennessee, where they were subjected to irradiation for a period of two weeks. Specific activity at the commencement of the tests was approximately 800 counts per minute per milligram, an activity which proved very convenient. By the time the tests were completed, a good approximation of the activity of the irradiated fingers was known by comparing, during the tests, the amount of weight transfer with the activity transfer.

A different technique was used to confirm the approximations. A known amount, about 100 milligrams, of a finger was dissolved in hydrochloric acid and this solution was diluted to 25 millileters. Then one hundredth part of this solution was micropippetted onto the surface of the sleeve used during the tests. The sleeve was then checked for radioactivity in the same manner as had been done during the tests. Correlation with the specific activity obtained during the tests was very good when correction was made for decay in activity over the period of the tests. Figure 12 shows the geiger tube, motor for rotating the sleeve during counting, and the lead enclosure.

(D) AN UNSUCCESSFUL RADIOACTIVE TECHNIQUE

Prior to having the fingers service irradiated, another method of activating the fingers was attempted. Two millicuries of Fe^{59} in a solution of hydrochloric acid were available and an attempt was made to electroplate this onto a set of fingers. No difficulty was encountered with the radioactivity itself, but considerable difficulty was encountered in making a satisfactory plating of the iron onto the steel fingers. Finally 4 fingers were successfully plated with a thickness of approximately .001 inch. These were never used due to the expense of obtaining additional isotope and the difficulty of further plating. The service irradiation of the complete finger proved much more inexpensive and satisfactory to test.

(E) ALIGNMENT OF TEST PIECES

Particular attention was paid to the alignment of the two mating test pieces when assembling for test. Tolerances were kept very close in manufacture and provision was provided for accurate final alignment in place just prior to or during the tests by means of set screws and

shims. Before a test, the two surfaces were brought together and alignment checked carefully by noting any light between them and this light eliminated by small adjustment of set screws. In one or two cases small adjustment was necessary after the first running period, but generally this alignment procedure produced an almost symmetrical wear scar without further attention during the run.

(F) ATMOSPHERIC SUPPLY

An atmosphere of filtered dry air was provided during the test. This was obtained by running compressed air through two 36 inch long glass tubes containing calcium sulfate desiccant and then through a cotton and glass wool filter. Finally the air was run through a copper coil immersed in liquid air. This then was lead through a rubber hose to the atmospheric chamber described above. During the radioactive tests, air coming from the atmospheric chamber was lead by hose to a hydrochloric acid bath through which it was bubbled. This was done in order to dissolve any entrained radioactive material that might be picked up in passing through the chamber. The air supply, except for the liquid air system, can be seen in Figure 9.

3. Procedures

(A) OUTLINE OF METHOD

The prime aim throughout the procedure was to maintain uniform conditions in so far as possible from one test to the next, since it is generally recognized that the slightest change in conditions produces radically different results. In spite of these precautions, it can be seen from Figures 13-18 that wear curves were not completely reproducible even though equilibrium wear rates were essentially so.

Prior to a test, both the finger and the sleeve were carefully cleaned with acetone and then weighed on an analytical balance. This was done as close to actual start of test as possible. The pieces were then assembled taking care to assure alignment of the finger face to the axis of the sleeve. After the desired length of run, both the sleeve and the finger were removed and reweighed, noting the change in weight of each. During the first six (non-radioactive) tests, the scar on the finger was measured both in depth, width and length. The depth was measured by the change in focus of a 445x compound microscope and the width and length were measured by the use of a 50x toolmaker's microscope. The weight removal was then computed from the volume removal and was found to be within 5% of the weight found by weighing. Due to variation in scar shape, it was decided to use the weighing method only on the last six tests.

An analytical balance was used for all weight measurements. This balance had a sensitivity and accuracy of 0.1 milligram. The approximate weight of the finger was 8 grams and that of the sleeve approximately 37 grams. The maximum amount of wear measured on each finger was about 15 milligrams and the amount of transfer detected on the sleeve was about 3.3 milligrams.

(B) AN UNSUCCESSFUL OPTICAL METHOD OF SCAR DEPTH DETERMINATION

Another method of measuring the depth of the wear scar very accurately was investigated rather extensively, namely the use of the channeled spectrum. An optical flat, about 20-30% vacuum aluminized, was placed on top of the wear scar with the aluminized surface against the metal. This then was illuminated by a spotlight. Light from both the bottom of the metal scar and from the aluminized glass flat (surface of the metal finger) was then reflected into a spectrometer by a suitable arrangement of reflecting and condensing lenses. The spectrometer enabled one to determine the difference in path lengths of the two incoming light sources and by counting fringes, to determine the amount of this path difference. This very accurately determined the scar depth. Unfortunately certain difficulties were involved. The method was actually too accurate and the surface of the bottom of the scar became a major consideration and it was difficult to determine exactly which fringes were the desired ones. Also it was difficult to eliminate any gap between the glass flat and the metal. Lastly, and the most difficult, was that, as wear proceeded, the bottom of the wear scar became darker and would not reflect sufficient light to produce fringes. This method was not used for any tabulated results.

(C) VARIATION OF PARAMETERS

After the first six runs with an inert finger, using the methods described above, the same tests were rerun using a radioactive finger and weighing the finger for change in weight, but placing the sleeve in a lead enclosure, shown in Figure 12, in order to count its activity with a Geiger tube and scaler counter. On tests shown in Figures 17 and 18 data

were obtained by both counting and weighing of the sleeve, thus establishing the specific activity of the fingers. On the first four tests simultaneous counting and weighing was done only sufficiently to obtain specific activity measurement of the finger material.

A total of twelve tests was made, with three variations of load - 300,600 and 900 grams and with two variations of speed - 200 and 400 rpm. Each of the six separate tests with an inert finger was repeated with a radioactive finger. Increases in load were made by adding weight to the top of the finger holder. The holder is shown without weights in the top center of Figure 10.

Throughout this work, wear refers to the material, either non-radioactive or radioactive, removed from the finger during the tests. Transfer refers to that material transferred from the finger to the hard sleeve and measured on the sleeve by either its increase in radioactivity or its increase in weight. Sleeve weight change refers to transfer measured by the change in weight of the sleeve as done primarily in the non-radioactive tests.

4. Results

(A) THREE REGIMES OF WEAR

Throughout the tests, three distinct regimes of wear existed. The first was the initial phase when both pieces showed the effects of wear, but there was no discoloration and it appeared to the naked eye to be more of a plowing interaction between the two surfaces. Figures 1 and 5 show the pieces prior to being worn and Figure 1 also shows the finger after being run for one minute. Although not detectable by the unaided eye, nevertheless, Figure 1 shows a definite discoloration taking place and this discoloration is assumed to be a compound formed during the process.

The first phase is characterized by a relatively lower wear rate as shown in Figures 19-22, and it is believed that the wear from the softer finger is completely deposited onto the harder sleeve without any loose wear debris being formed. This is substantiated by no wear debris being formed as seen during the tests and by the general coincidence of the wear and transfer curves during this period as shown in Figures 13-18.

Depending on load and speed, a second very short phase commences within about 4000 revolutions of the start of the tests. This phase is quite transitory in nature and is characterized by the formation of a black wear product, assumed to be an oxide of iron, Fe_3O_4, magnetite, which is loosely adherent to the finger and the sleeve. This product is visible to the unaided eye and in the microscope and while to the unaided eye it seems to disappear in the next phase, the microscope shows it present in very small quantity during the remainder of the tests. This phase shows the beginning of the rise of both the wear and the transfer

rates, as shown in Figures 13-18. Its start is believed delayed by the surface film on the finger and sleeve which must be worn away. Even though extreme care was taken to insure uniformity of surface conditions prior to test, many workers have found that an oxide film is formed almost instantaneously on a piece of steel after cleaning or polishing, and is always present prior to starting a test. It is believed that while the figures show this phase to start sooner with increased load and increased speed (non-existent at 900 grams, 400 rpm as shown in Figure 18) that nevertheless for tests under the same conditions of speed and load, the number of revolutions at which this phase starts, varies considerably. This is believed to be due to variation in surface conditions at start of test.

The third and final phase is characterized by the formation of a red oxide of iron, believed to be Fe_2O_3 , hematite. Shortly after the commencement of this phase, the transfer quickly reaches a maximum equilibrium condition and does not further increase. The wear rate also reaches an equilibrium and stays constant at greater than the initial rate to any length of test. This red wear debris is loosely adherent, may be wiped off with a cloth, and results in scattering of wear debris off the wear pieces. This debris is shown in the darkest section of Figures 2-4 and 6-8 .

In an attempt to more accurately identify the wear product of the equilibrium condition, Kerridge took x-ray powder photographs and showed that it was either hematite (Fe_2O_3) or hydrohematite ($Fe_2O_3 \cdot nH_2O$) , the diffraction patterns of which are similar. He also made wear tests in a vacuum at a pressure of 10^{-3} mm of mercury. In these tests only very small amounts of this red wear product were discerned.

(B) EQUILIBRIUM PHASE OF WEAR VARIES WITH SPEED

In general the three phases described above were present for all the variations in load and speed, but at the higher speed (400 rpm) a variation on the third phase, or an entirely different phase, appeared very shortly after the third phase described above. This variation does not appear on any of the curves except possibly Figure 23 but it does find support in the photomicrographs of the sleeve shown in Figures 6-8. In the low speed tests, the sleeve gradually increased in redness and it appeared to gather more transfer. It reached a maximum as seen by the eye at about the same time the transfer curves reached their maximum. However, on the higher speed tests, this same process occurred, but shortly after the maximum was reached, it suddenly lost its dark red appearance and appeared polished, as if it had suddenly lost all its transferred material. This appearance then remained during the rest of the test.

To the eye and to the microscope, since the color was due to the loosely adherent transfer, it would seem that this loss in color would show up in both loss of activity and in loss of weight of the sleeve. No such evidence exists as can be seen for the 400 rpm transfer curves as shown in Figures 16-18 and compared in Figure 25.

(C) ANALYSIS OF WEAR CURVES

From observing the comparative wear curves for various speeds and loads as shown in Figures 19-22, the following is found to be generally true:

(a) the amount of wear increases with number of revolutions, but the wear rate is essentially constant after reaching an equilibrium condition.

(b) the final wear rate is greater, the greater the load, but this effect is more pronounced at higher speed.

(c) the knee in the wear curve occurs at a greater number of revolutions for less load to the point of almost no knee for the high speed and high load test. While wear rates are consistent between runs of the same conditions, the knee is not always consistent.

(d) wear rate remains constant with increasing area of contact, showing wear is independent of area of contact.

(D) ANALYSIS OF TRANSFER CURVES

From observing the comparative transfer curves at various loads and speeds as shown in Figures 23-25 , the following is found to be generally true:

(a) all the wear from the finger is transferred to the sleeve during the initial wear phase. Shortly after the end of this first phase, at the point where the wear rate increases, loose wear debris commences being formed.

(b) very shortly after the red debris product starts being formed, the radioactive transfer reaches an equilibrium maximum and remains constant no matter what amount of wear is produced. This is seen not only from the curves, Figures 13-18, but was also observed generally during the tests.

(c) from Figure 23, the weight change of the sleeve is dependent on both load and speed, unlike the radioactive transfer as shown in Figures 24 and 25 . However, in the slower speed tests the weight change reaches an equilibrium maximum as in the radioactive transfer.

(d) from Figures 24 and 25, the maximum amount of transfer is

essentially independent of load and speed, although in one test the transfer did run considerably higher.

(e) from Figure 23, the weight change of the sleeve increased to a maximum positive value and then, dependent on load, decreased below its original weight, even though, as seen from Figures 24 and 25, its activity remained high. This was true at all loads for the higher speed.

(f) as soon as an inert finger was substituted for the radioactive finger, the activity of the sleeve fell off at a very rapid rate even though the wear rate remained unchanged. Occasionally checks were made on the activity of the inert finger and it was constant at a very low amount almost from the moment of its beginning to run, showing very little back transfer of activity from the sleeve to the inert finger.

5. Discussion

(A) RADIOACTIVE METHOD

The radioactive portions of these tests are essentially as found by M. Kerridge and thus give rise to his theory of the component parts of the wear process. Since the initial wear and transfer rates are essentially the same, the wear from the finger is all being placed on the sleeve. This constitutes the first phase of the wear process and during it no wear debris is observed. The next phase is signalled by the appearance, first on the finger and then on the sleeve, of a black compound. At the same time the wear rate starts to rise and very shortly thereafter the transfer rate rises also. This second phase is quite transitory in nature and very quickly the third phase, as noted by the appearance of a red compound on the finger and then on the sleeve, appears. The third phase becomes an equilibrium phase in which the wear rate and the activity on the sleeve reach a constant value and then do not change.

A possible reason for the change in wear rate in the second and third stages is that abrasive wear is added to the adhesive wear of the first phase. The abrasive is the red and black compounds, formed as wear debris. Dana and Ford [6] report both Fe_2O_3 and Fe_3O_4 as having a hardness of 5.5 on the Mohs scale and this is sufficiently hard to form a very effective abrasive. That these compounds are oxides of iron has been generally accepted.

Another technique of Kerridge's which was tried, was the insertion of an inert pin for the radioactive pin, after the third phase was well established. As can be seen in Figures 14-16, this resulted in an immediate and radical drop in the radioactivity with no change in wear rate. This leads to the theory that all loose wear product comes from

the finger via the sleeve. The material is oxidized on the sleeve and then turned loose as wear debris and that no wear debris is produced directly from the finger. This means that the particle membership on the sleeve, while a constant in number, is constantly changing, new product being brought in from the finger while the old is being tossed off.

This led Kerridge to the very plausible theory of the parts of wear process, namely (i) welding of the two surfaces, (ii) transfer of softer metal to the harder surface, (iii) oxidation of this transferred material as a layer on the harder piece, (iiii) removal of this oxide to form wear debris.

(B) WEIGHT CHANGE METHOD

A variation in method was chosen to corroborate the radioactive transfer findings as described above. In this method both the weight change in the sleeve and the finger was measured. Assuming that the wear product formed on the sleeve is an oxide, it was expected that the increase in weight of the sleeve would be greater then the wear from the finger and also greater than the weight increase of the sleeve as given by the activity increase. The reason for the expectation was that the weight increase would measure the added oxygen from the air in forming the compounds. As can be seen in Figures 13-18, this was not in fact the case, but rather the weight change generally coincided with the activity transfer from the finger, especially during the first phase when the wear was entirely transferred.

(C) UNEXPECTED RESULTS

Referring to Figures 23-25, it is noted that the sleeve weight change at 200 rpm shown in Figure 23 is not radically different from the transfer of activity shown in Figure 24. However, noting the sleeve

weight change at 400 rpm shown in Figure 23, it is seen to vary radically from the transfer of activity as shown in Figure 25, in that after reaching a maximum approximately the same as that indicated by the activity transfer, it starts to decrease linearly, falling below the original sleeve weight. This would indicate that despite the hardness advantage held by the sleeve, at the higher speed it commences to wear some time in the third phase.

This phenomenon does not seem to be in any way connected with the commencement of any wear phase. The third phase (and appearance of red oxide) commences sooner, the higher the load, whereas the wear of the sleeve commences essentially the same time independent of the load. A basic reason for the existence of the phenomenon at all at the higher speed could be that the high temperatures, mentioned above, anneal the heat treated sleeve asperities to the point that their hardness is radically reduced. This condition could exist in very minute areas just as the temperature flashes are confined to very small asperities. Bowden and Tabor found that temperature varied directly with velocity so that the higher speed would definitely produce a considerably higher temperature. On the other hand they found that temperature varied directly with weight also, and this would not explain the fact that the weight did not appear to effect the point at which this phenomenon occurred.

Another possible explanation is that the oxide film which remains in place at 200 rpm and which is removed to give a polished surface at 400 rpm, prevents the sleeve from being worn at the lower speed.

6. Conclusions

1. Three distinct wear regimes exist under the conditions of these tests. These phases are distinguished by their wear product, or lack of it, and by different wear rates. Phase one shows no compound formation and is assumed to be simple adhesive wear at the lowest rate of wear. Phase two shows an increase in wear rate and a black compound is formed. Phase three shows an equilibrium condition of wear rate and of total transfer to the harder sleeve, is characterized by a red compound formation, and consists of both adhesive and abrasive wear.

2. These tests confirm the work of Kerridge and therefore support his very plausible theory that the wear process is composed of various parts: (i) welding of the two surfaces, (ii) transfer of softer metal to the harder surface in breaking the welds, (iii) oxidation of this transformed material as a layer onto the harder piece, and (iiii) the removal of this oxide to form a wear debris.

3. Another phenomenon goes on, seemingly separately from the wear process as described by Kerridge and undetected by the radioactive means. This process is a wearing away of the harder sleeve at higher speed, a process that does not occur at the lower speed used in these tests. It appears to be dependent on speed, but not in any way directly connected with the wear process going on in the softer fingers.

It must be emphasized that the findings and conclusions of these tests are applicable only to the exact conditions used in these tests.

Fig. 1 FINGER, magnification 780x, 1 minute run with 900 grams load at 400 RPM. Lower left shows unworn section. Remainder shows plowing action of hard sleeve and beginning of formation of black wear product.

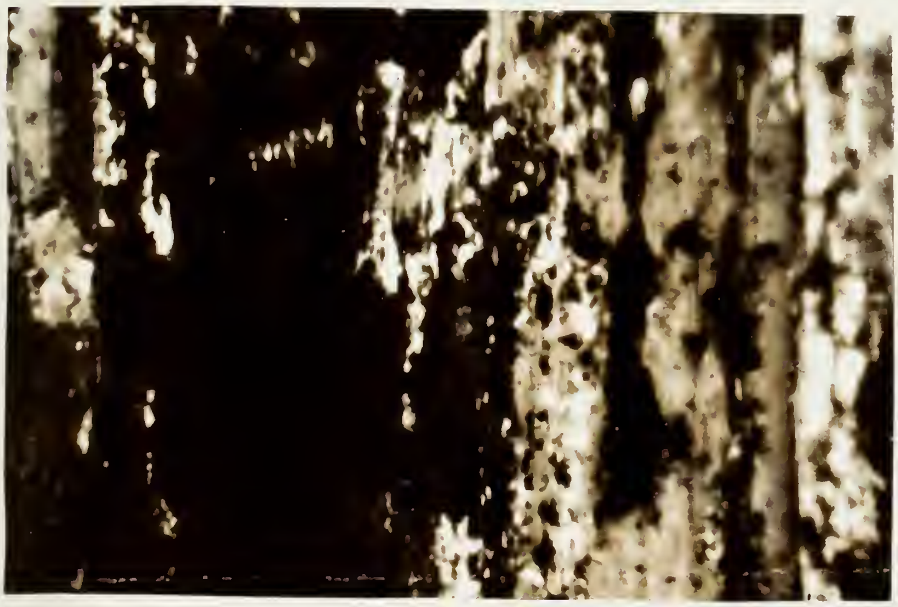

Fig. 2 FINGER, same as above after 11 minutes. Very dark sections are rust red wear product, lighter areas are grey and very light sections are unworn.

Fig. 3 FINGER, same as fig 2 after 15 minutes.

Fig. 4 FINGER, same as fig 3 after 18 minutes. Dark areas of rust red wear product have almost completely disappeared due to polishing action.

Fig.5 SLEEVE, manification 160x, unworn.

Fig. 6 SLEEVE, magnification 160x, 5 minutes run with 900 grams load at 400 RPM. Dark areas are powdery black wear product thinly spread.

Fig. 7 SLEEVE, same as fig. 6 after 11 minutes. Dark areas are rust red wear product. Lighter areas are thinly spread black product.

Fig. 8 SLEEVE, same as fig. 7 after 15 minutes. Dark areas have almost completely disappeared and small remainder gives a polished red appearance. Lighter areas are thinly spread black product.

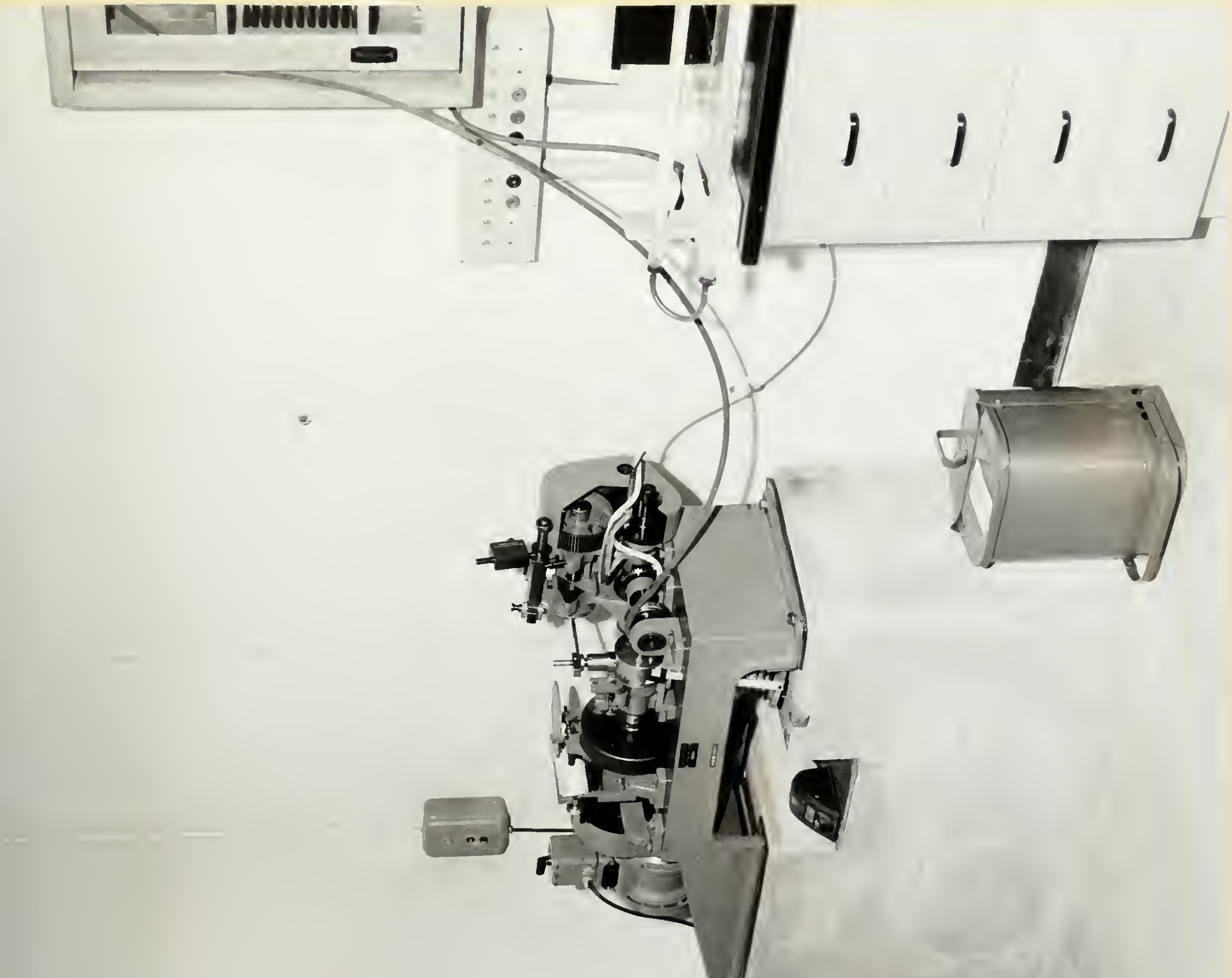

Fig. 9 General View of Test Area, showing radiation counter, balance, Amsler Wear Test Machine, and air drier.

Fig. 10 Details of finger and sleeve without atmospheric chamber in place

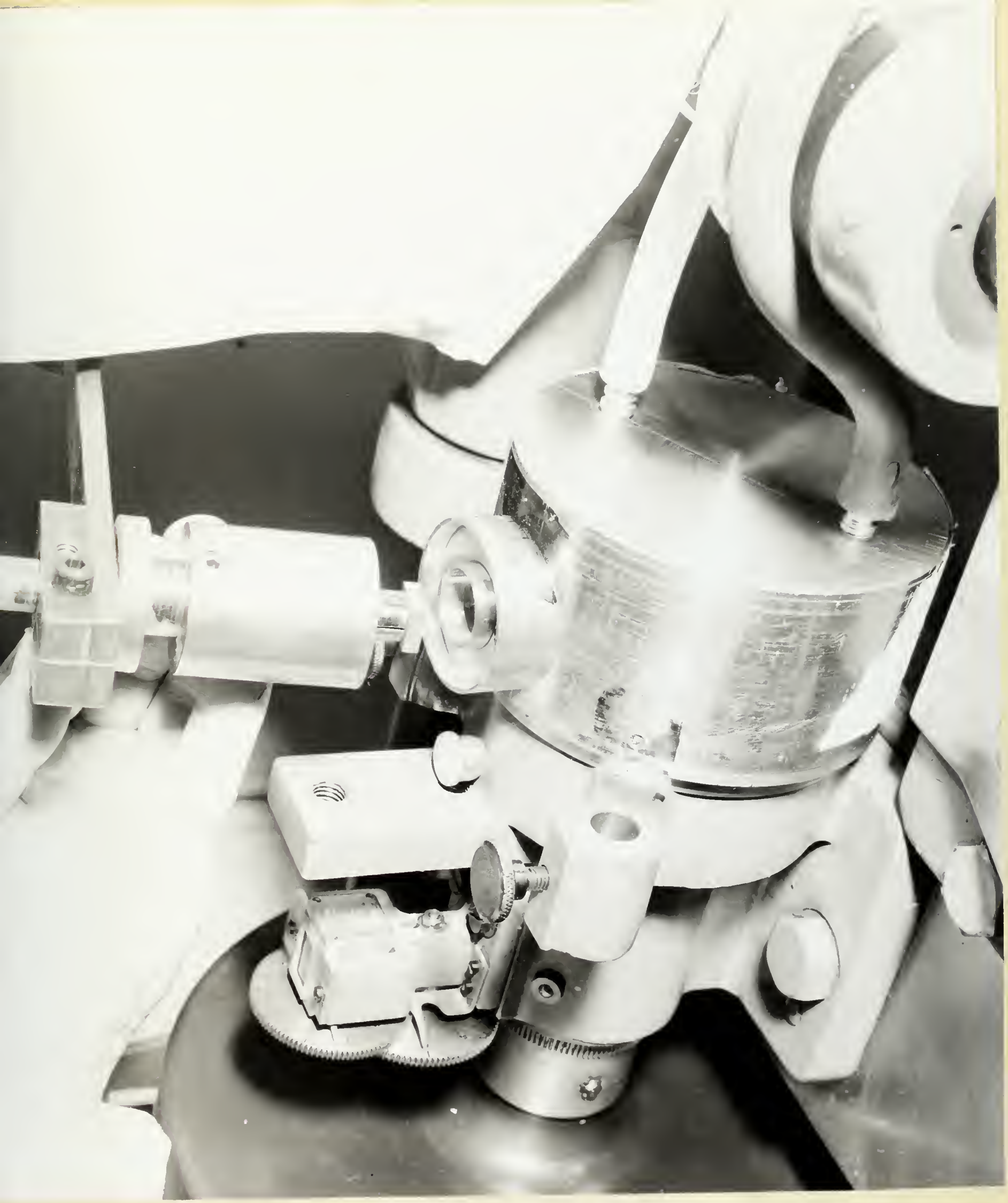

Fig. 11 Details of finger, atmospheric chamber with its oil seal at top, and hose leads in and out of chamber.

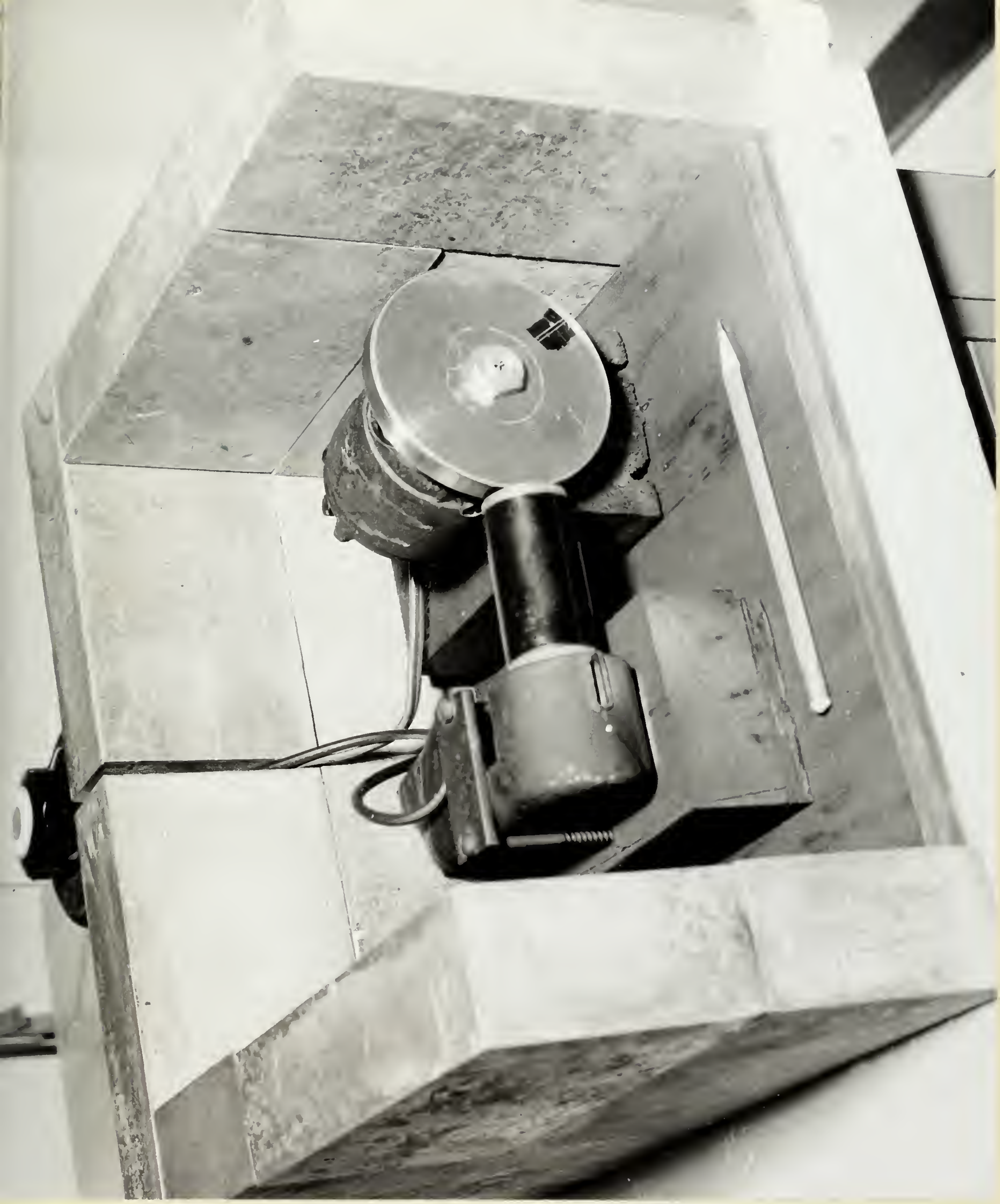

Fig. 12 Details of Geiger tube, sleeve in position for irradiation measure, motor for rotating sleeve, and lead enclosure.

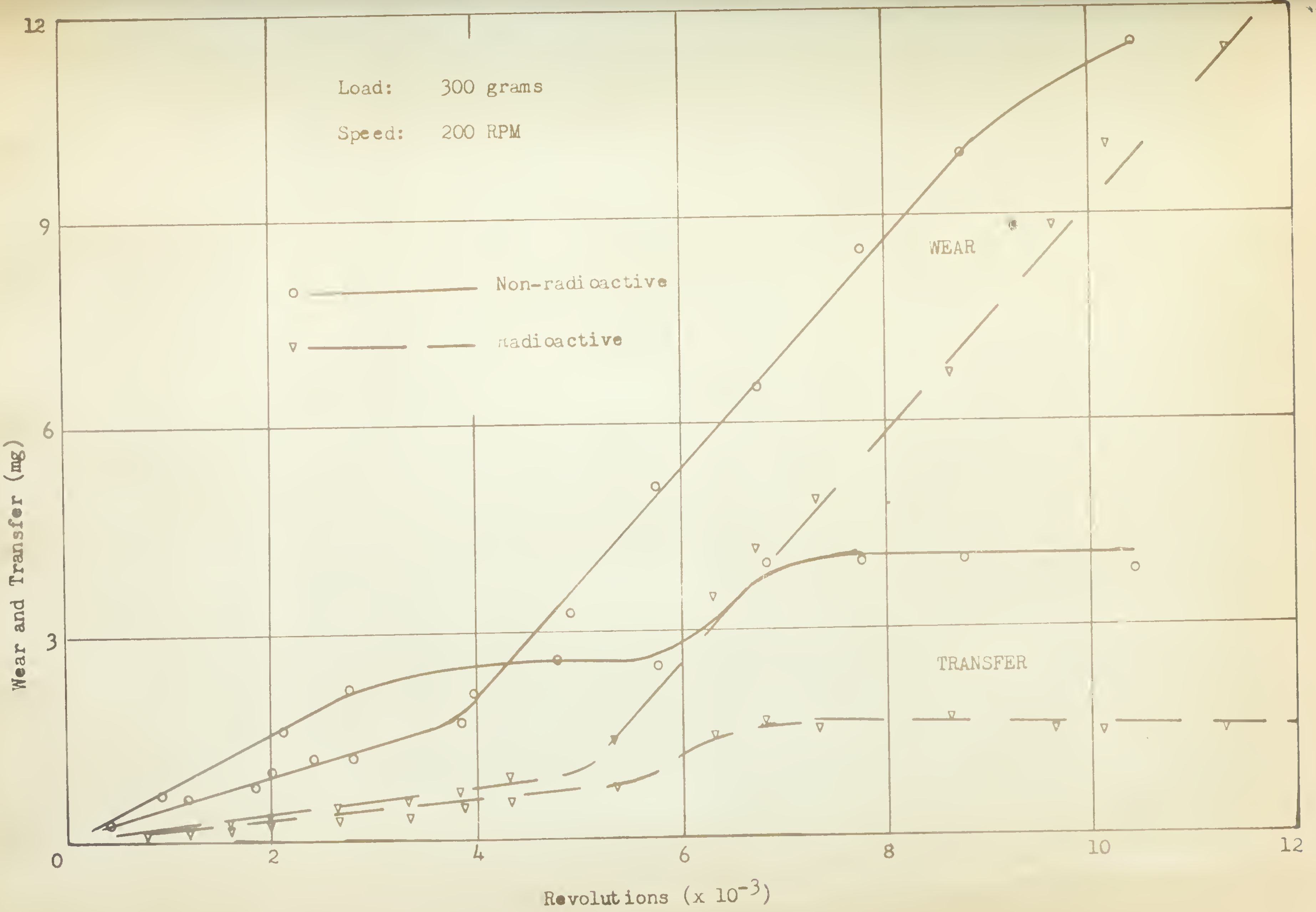

Fig. 13 - WEAR AND TRANSFER x REVOLUTIONS

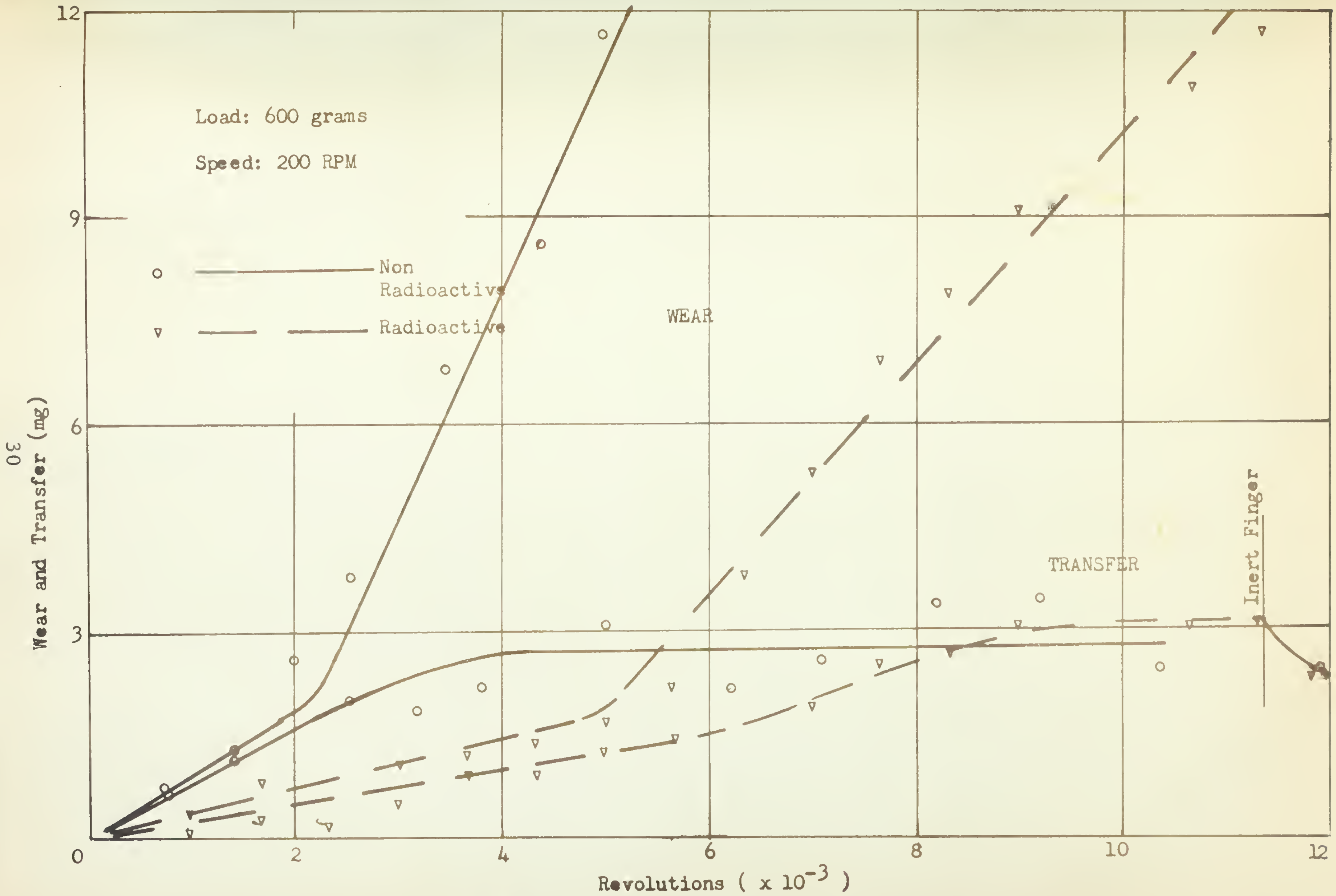

Fig. 14 - WEAR AND TRANSFER x REVOLUTIONS

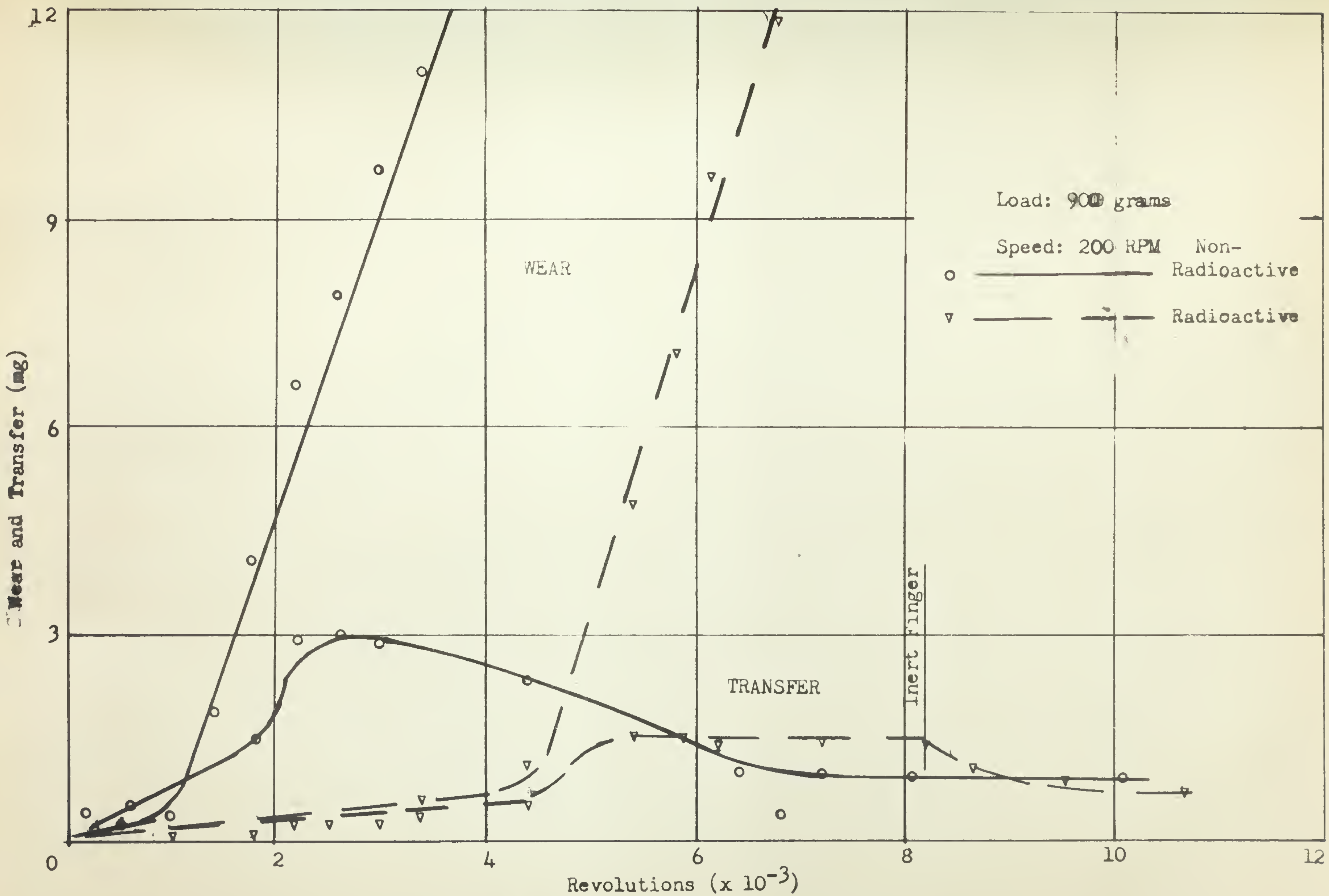

Fig. 15 - WEAR AND TRANSFER x REVOLUTIONS

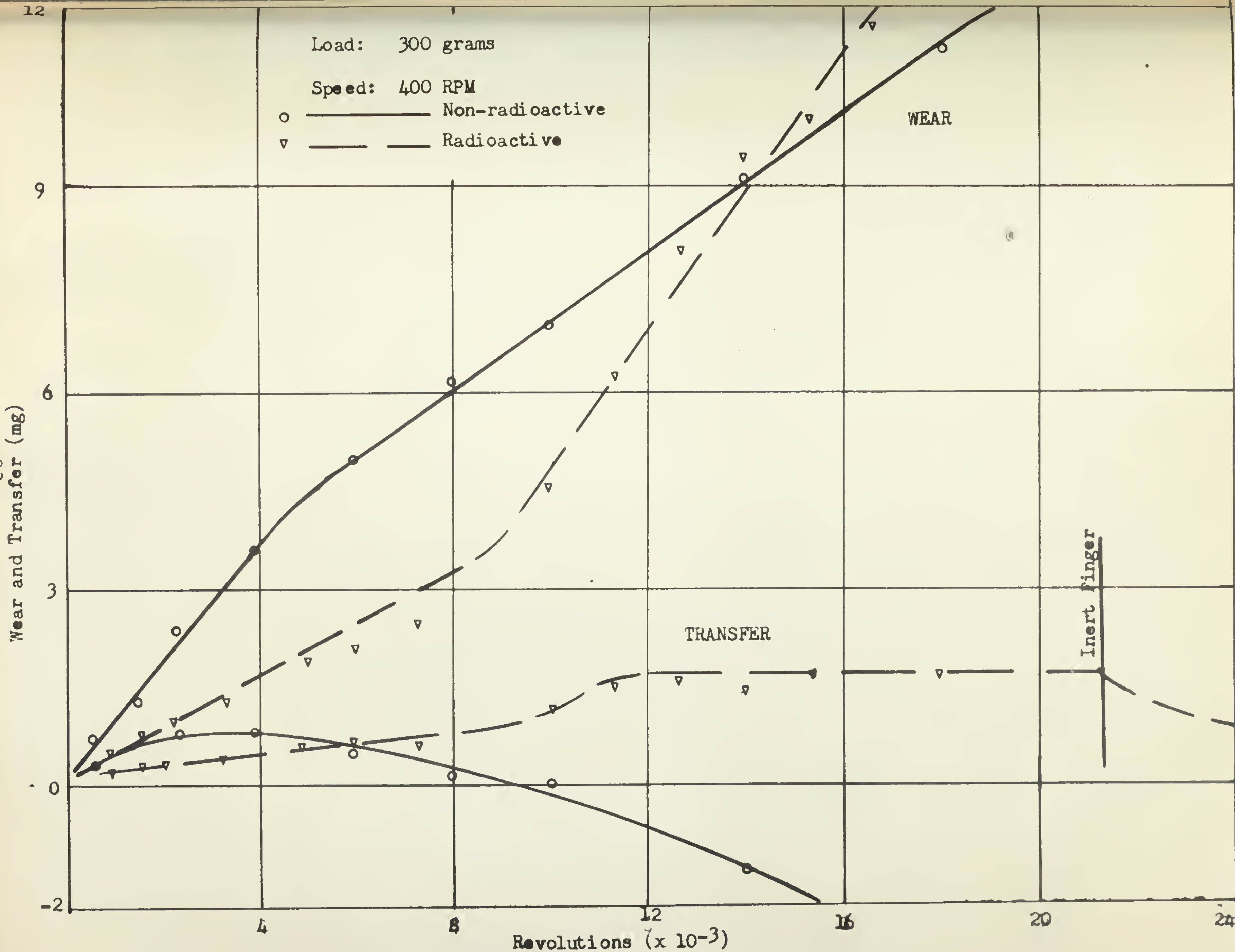

Fig. 16 - WEAR AND TRANSFER x REVOLUTIONS

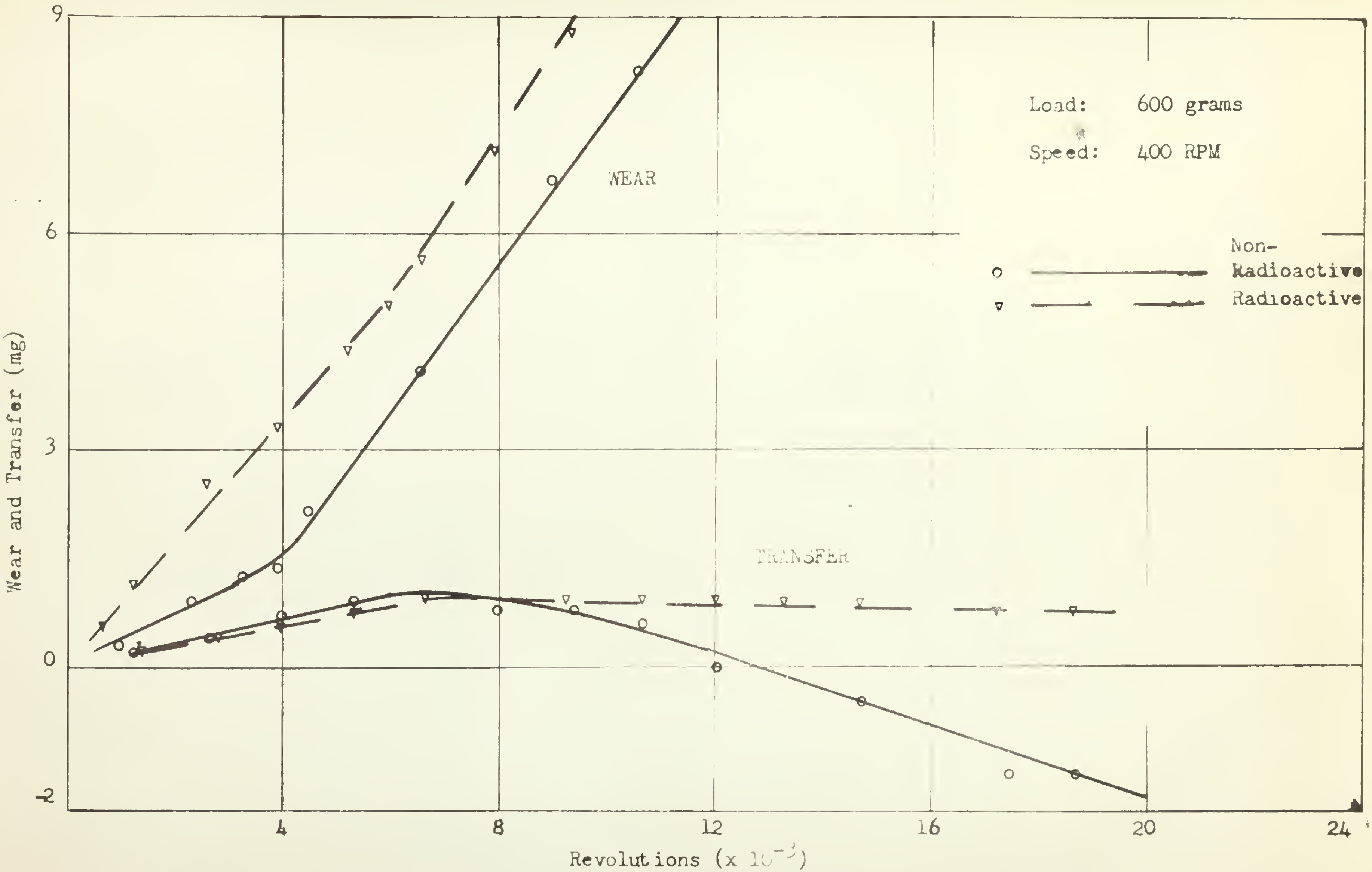

Fig. 17 - WEAR AND TRANSFER x REVOLUTIONS

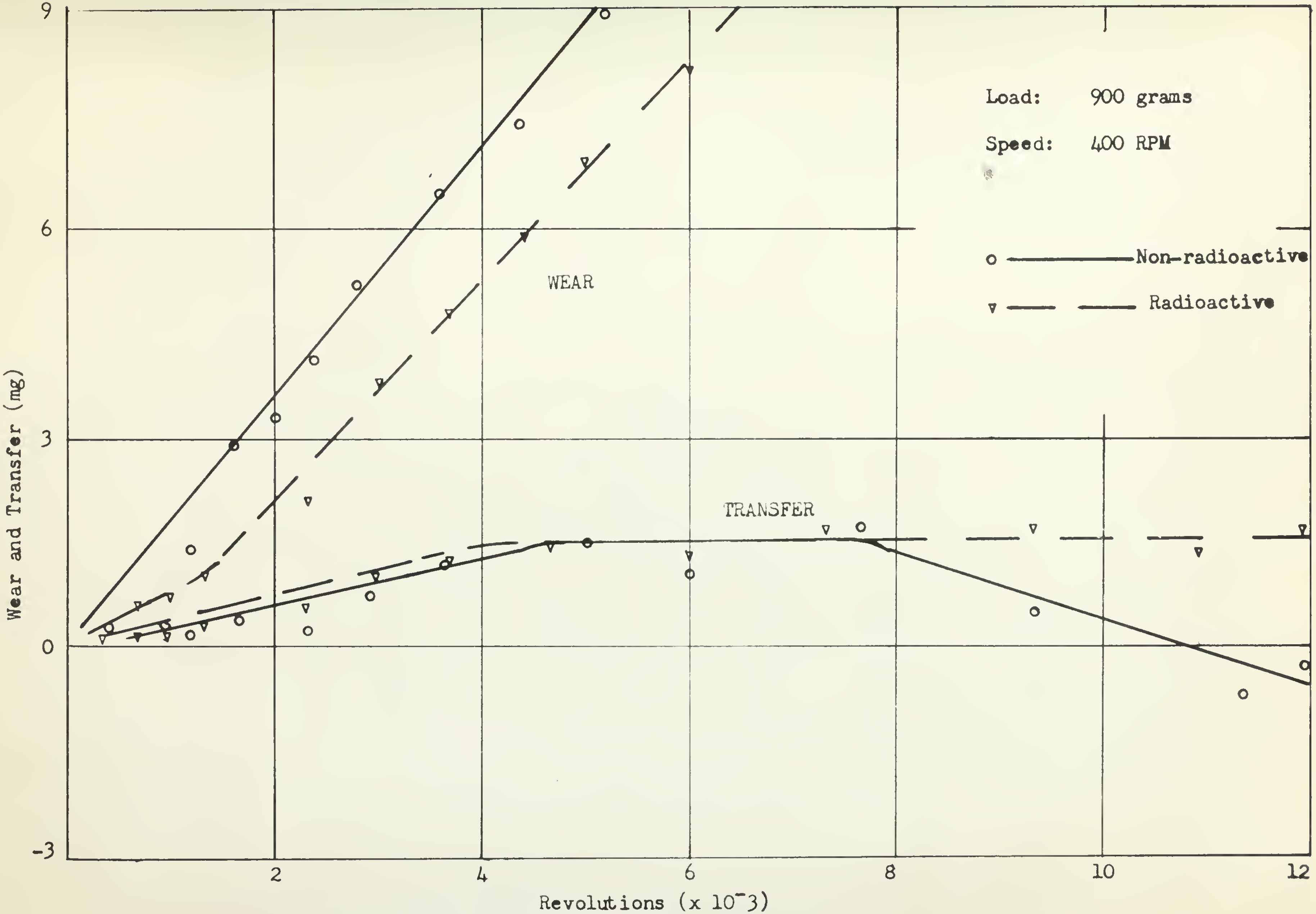

Fig. 18 - WEAR AND TRANSFER x REVOLUTIONS

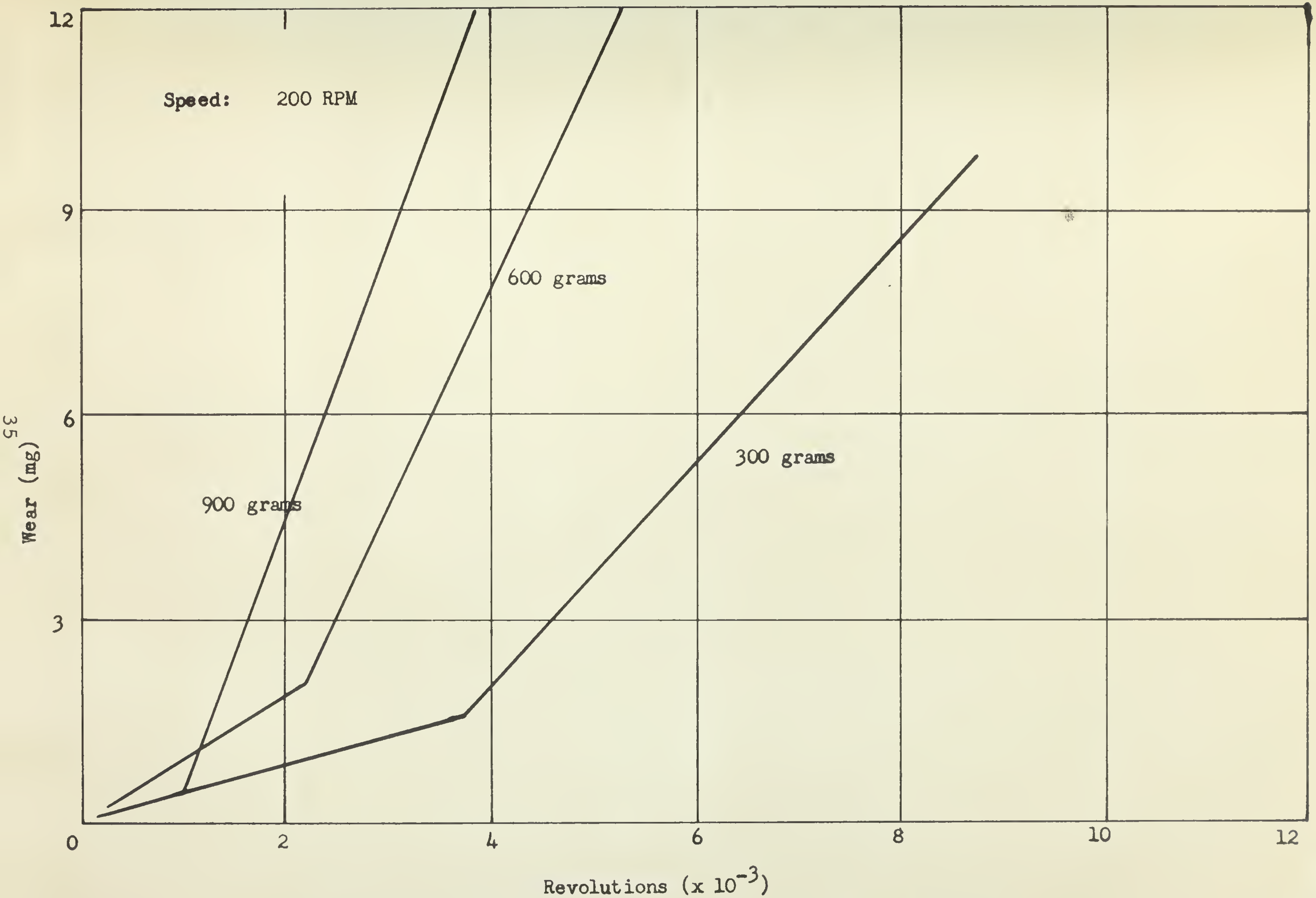

Fig. 19 - WEAR x REVOLUTIONS ON NON-RADIOACTIVE TESTS

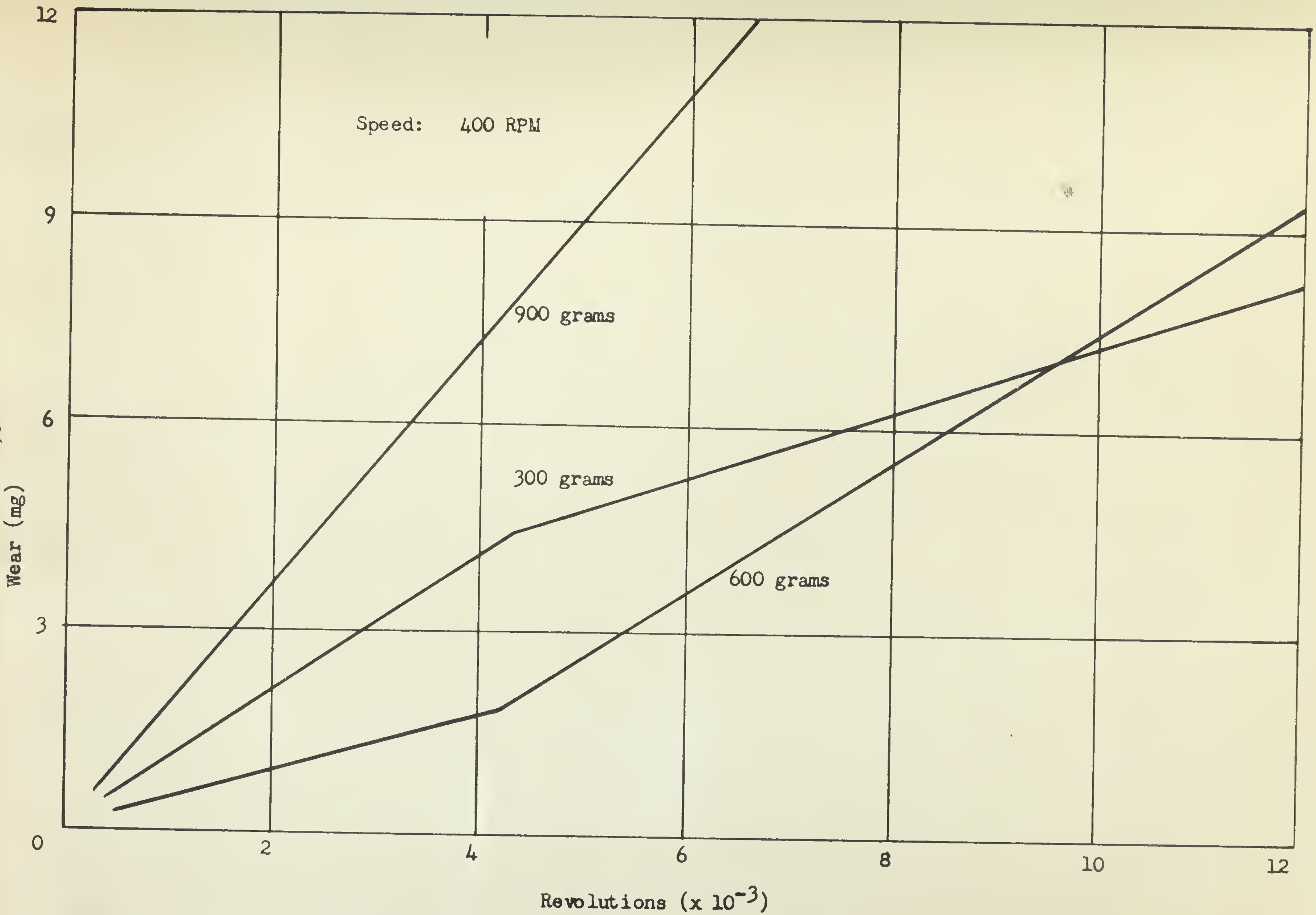

Fig. 20 - WEAR x REVOLUTIONS ON NON-RADIOACTIVE TESTS

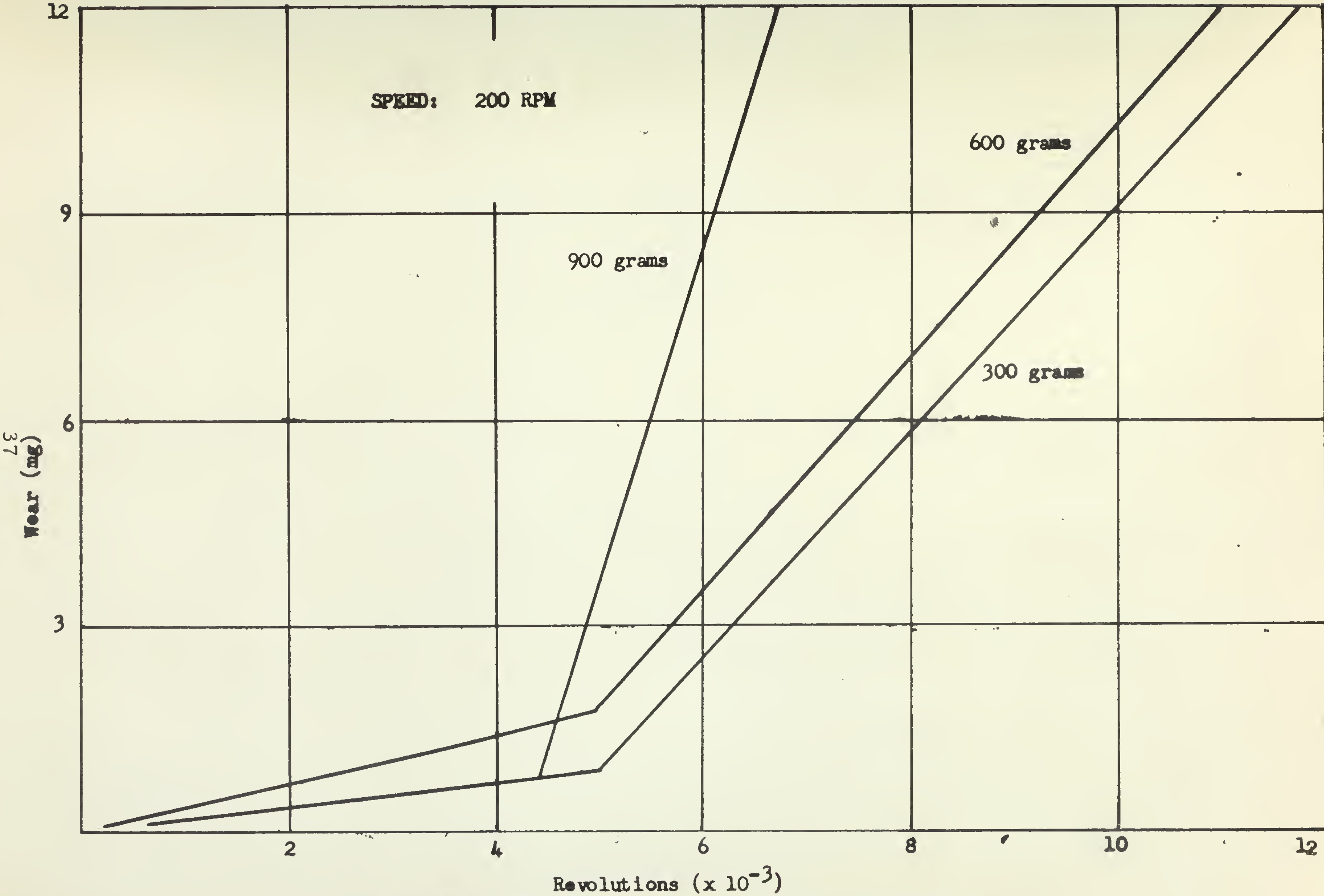

Fig. 21 - WEAR x REVOLUTIONS ON RADIOACTIVE TESTS

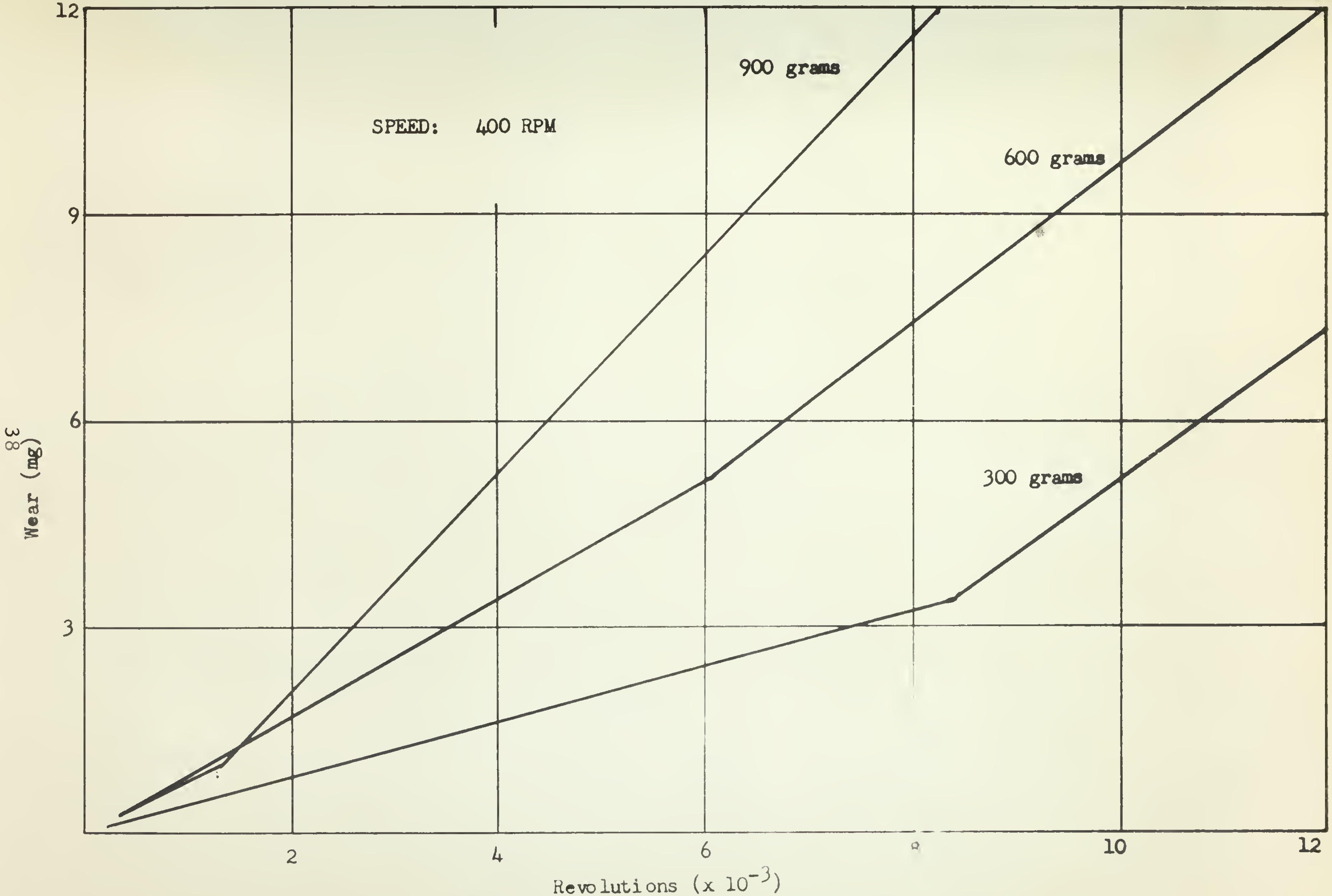

Fig. 22 - WEAR x REVOLUTIONS ON RADIOACTIVE TESTS

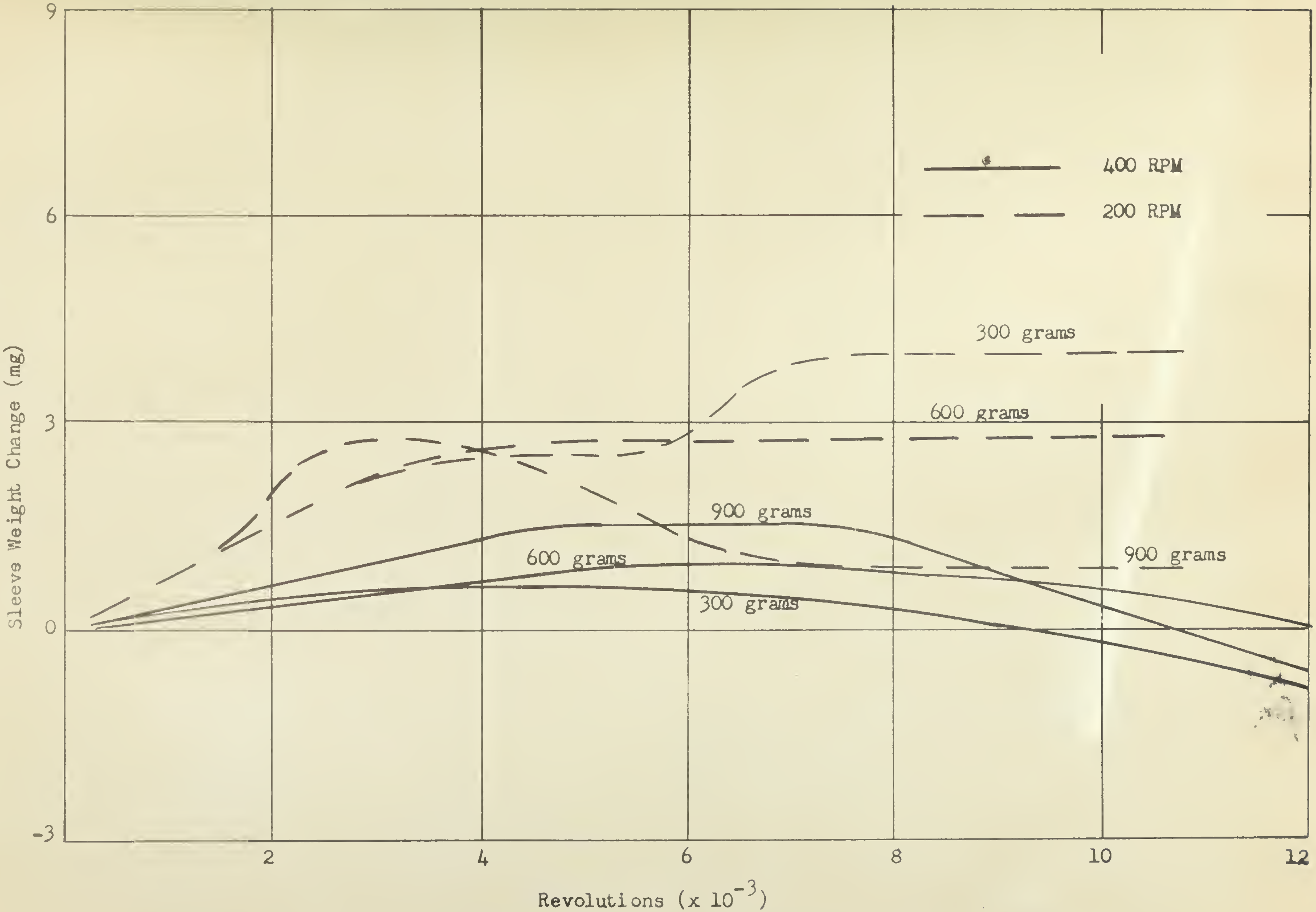

Fig. 23 - TRANSFER AS MEASURED BY WEIGHT CHANGE METHOD - COMPARISON

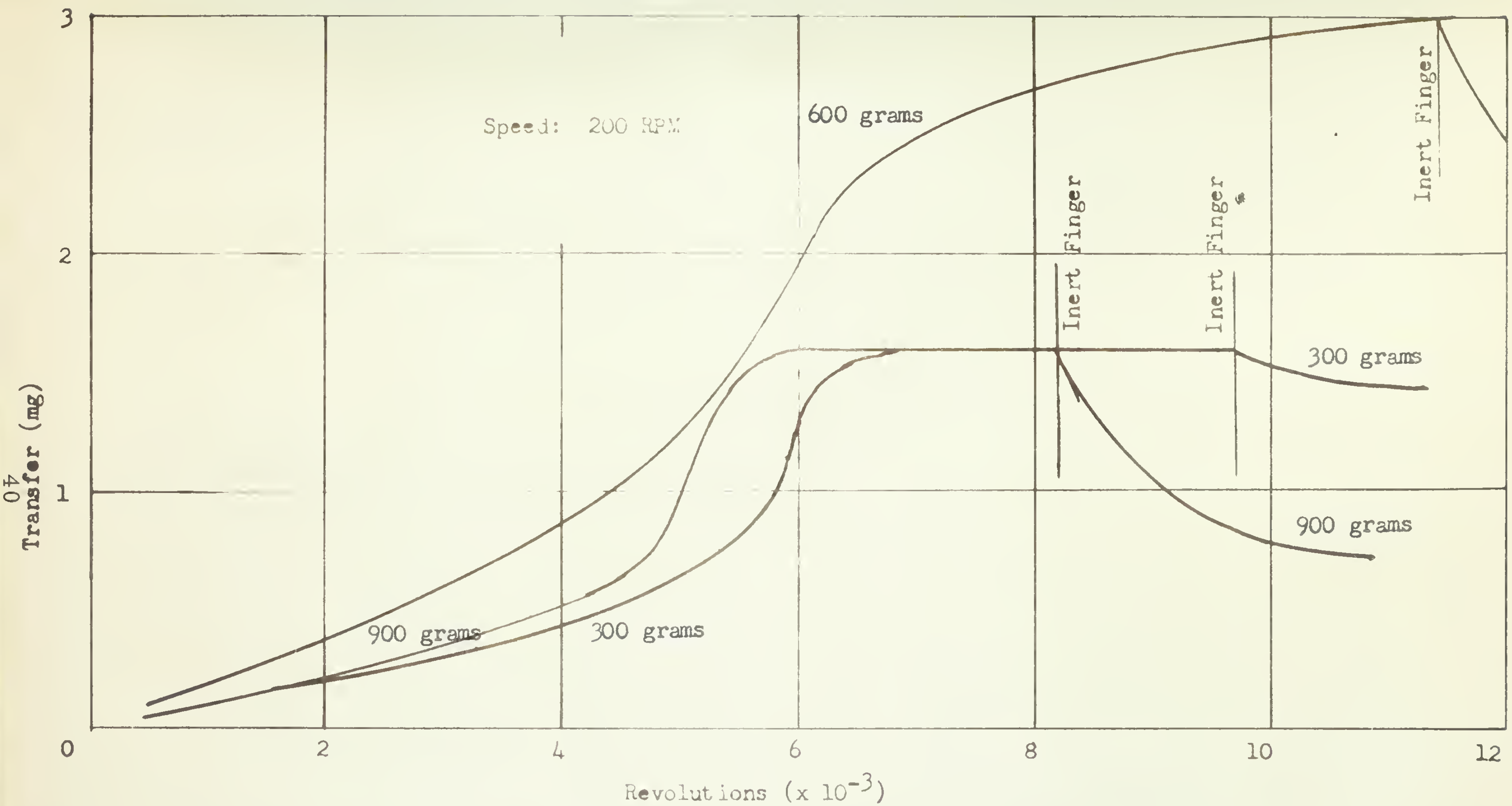

Fig. 24 - RADIOACTIVE TRANSFER x REVOLUTIONS

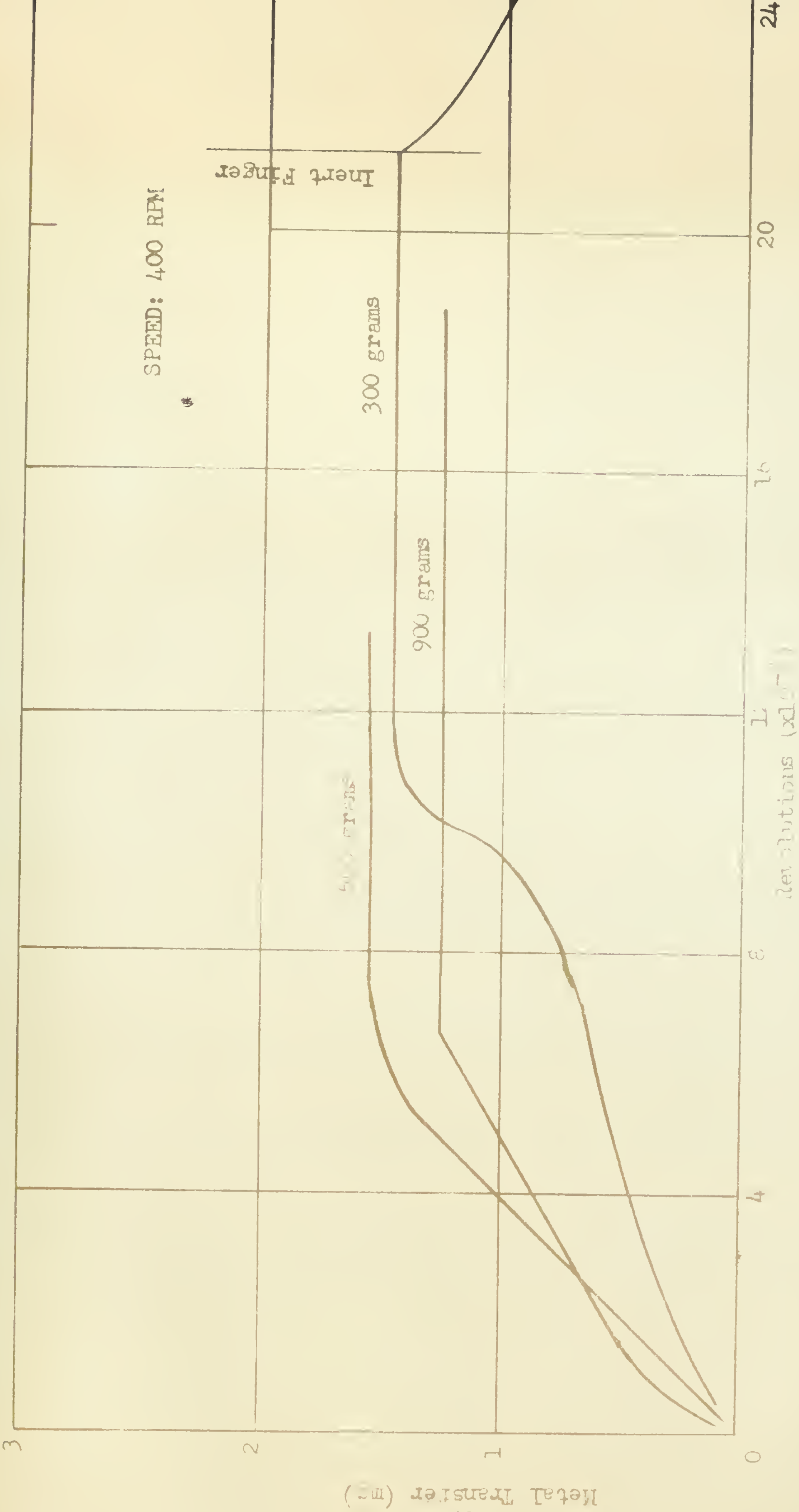

Fig. 25 - RADIOACTIVE METAL TRANSFER COMPARISON

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